1971

Design of a shipboard pollution control system.

Maxham, John Charles.

Massachusetts Institute of Technology

DESIGN OF A SHIPBOARD
POLLUTION CONTROL SYSTEM

by

John Charles Maxham

DESIGN OF A SHIPBOARD POLLUTION CONTROL SYSTEM

by

JOHN CHARLES MAXHAM

B.S., United States Coast Guard Academy

(1966)

SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE

DEGREES OF NAVAL ENGINEER AND

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF

TECHNOLOGY

May 1971

DESIGN OF A SHIPBOARD POLLUTION CONTROL SYSTEM

by

JOHN CHARLES MAXHAM

Submitted to the Department of Naval Architecture and Marine Engineering and the Department of Mechanical Engineering on 14 May 1971 in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Mechanical Engineering.

ABSTRACT

The problem of combating shipboard water pollution is becoming an increasingly urgent one. This thesis analyzes the shipboard pollution problem presented by a particular ship in three major areas: (1) Solid Wastes; (2) Sewage Wastes; and (3) Ballast, Bilge, and Machinery Discharges.

A system consisting of an incinerator, a chloroflotator, a coalescer/filter unit, and associated equipment is proposed for the ship, after an investigation of available methods of waste disposal. The state-of-the-art of some of the equipment chosen requires that further development and testing be carried out, but this system should be feasible in the very near future.

An examination of the effect of placing this system on the ship finds that stability and other hydrostatic properties are not impaired, and that the ship should encounter no difficulty in carrying this system.

Thesis Supervisor: A. Douglas Carmichael
Title: Professor of Power Engineering

ACKNOWLEDGEMENTS

First, I would like to thank the United States Coast Guard for affording me this opportunity to further my education at the Massachusetts Institute of Technology.

I would like to thank my thesis supervisors, Professor A. Douglas Carmichael and Professor David G. Wilson, for their assistance and patient guidance.

I would also like to thank the First Coast Guard District Engineering Division, Naval Engineering Branch, and the Engineering Department of the USCGC Chase (WHEC-718) for their assistance in obtaining data relating to the model ship.

Finally, a special thanks is due my wife, Rosalie, for her understanding, support, and efficient typing of this thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Increasing ecological awareness has caused man to look about him and examine his effect on his environment. Those seemingly infinite reservoirs--the air, the land, and the sea--are showing the effects of pollution.

For some time now, we have been aware that water pollution has affected many of our harbors and inland waters, but now the oceans themselves are beginning to show signs of the continued practice of dumping our wastes into them.

Thor Heyerdahl, in his most recent trans-Atlantic voyage, reported a "continuous stretch of at least 1400 miles of open Atlantic polluted by floating lumps of solidified asphalt-like oil." Oceanographers, such as Jacques-Yves Cousteau, report that many forms of sea life are disappearing. The oceans, which seem so vast to the ordinary man, are not immune to contamination.

The blame for pollution of our oceans and harbors must, in some part, be placed on ships, which now have the capability to pollute at a rate in the millions of tons per year. This pollution may result from ship damage, such as collision or grounding, but these are isolated cases; more likely, it results from the practice of dumping unprocessed wastes, solid as well as liquid, over the side. It is this latter problem that this thesis proposes to examine.

The purpose of this thesis is to present a design for a shipboard system capable of disposing of these wastes without harm to the environment. In order to do this, the types

and quantities of wastes must be determined; methods of disposal must be sought and analyzed; the phrase "without harm" must be examined, taking into account the legal requirements, to evaluate the quality required; salient features of the system must be decided upon; and finally a systems analysis must be performed to choose the optimum system to do the job satisfactorily. This done, the system must be sized and effectively placed on a vessel.

The Coast Guard 378' high endurance cutter was chosen as the vessel on which the system would be placed and operated.

SELECTION OF THE MODEL SHIP

It seems appropriate that the reasons for selecting the Coast Guard high endurance cutter be explored in more detail, since this will be the base from which the problem will be developed.

There are thousands of ships covering a myriad of sizes, types, and contributions to the total pollution problem. To cut through this wide spectrum and study the problem more specifically, one ship type was chosen. This ship type should be one which adequately represents all phases of the pollution problem, so that the extent of the problem can be determined, a solution proposed, and the effect of this solution on the ship investigated.

The 378', 2900 ton high endurance cutter is the Coast Guard's newest vessel. Her primary mission is ocean station

weather patrol, which lasts approximately 35 days port to port, and she carries a complement of about 150 men. While this vessel is not as large as some, the size of her crew and the length of her mission combine to create a sizeable solid and liquid waste problem. It is felt that due to its operational profile, this vessel is a fair representative of the ocean-going ships which have been creating the pollution problem.

Finally, four of these vessels are homeported in Boston, so data, such as it was, and plans for these vessels were readily available.

TYPES OF SHIPBOARD WASTES

Since there are a variety of waste products involved in this study, the first step will be to analyze them qualitatively, and attempt to break them down into logical categories, from which they may be dealt with as more-or-less separate entities.

Shipboard wastes are generated from many sources, but two means of discharging them into the sea are readily apparent. Wastes may be dumped or thrown over the side in a solid form, and they may be pumped or flushed from the vessel in a liquid or semi-liquid form. Therefore, the most immediate breakdown will be into solid and liquid wastes.

The liquid wastes, moreover, when further investigated, are of several types. An investigation of overboard discharges on the model ship discloses salt water coming from cooling systems, flushing systems for sewage and garbage, ballast and

bilge systems, and fresh water from laundry, galley, scullery, bathing facilities, and the like. Many of these liquid discharges have solids entrained in them.

As a final breakdown, the following basic categories were chosen:

A. Solid Wastes

Solid wastes are those wastes which are primarily solid in nature, and are composed almost entirely of trash and garbage.

B. Sewage Wastes

Sewage wastes consist of all human or non-machinery related wastes which are primarily liquids.

C. Ballast, Bilge, and Machinery Discharges

This category is self-explanatory, and the primary concern is oil pollution from these liquid discharges.

These categories are different enough to be analyzed separately, however each will undoubtedly have interactions with the others, so that the whole system may eventually be tied together. A similar breakdown of shipboard wastes is found in (1).*

A qualitative summary of the general character of the wastes generated by the model ship is presented in Table I.

---

*Numbers in parentheses refer to specific works listed in the references section.

TABLE I

QUALITATIVE SUMMARY OF SHIPBOARD WASTES

I. Solid Wastes

Paper and Cardboard
Garbage and Food Products
Rags, Cloth, and Line
Rubber and Leather Products
Plastics and Wood
Bottles, Glass, and Ceramics
Metals and Tin Cans

II. Sewage Wastes (discharges from)

Water Closets
Urinals
Showers
Laundry
Scullery
Galley
Drinking Fountains
Drains

III. Ballast, Bilge, and Machinery Wastes

Ballast Water
Bilge Water
Cooling Water
Evaporator Discharge

THE SHIPBOARD SOLID WASTE PROBLEM

The analysis of the shipboard solid waste problem has lagged behind that of the other areas, primarily because it is legal to dump solid wastes at sea, outside the navigable waters of the United States, and because, when in the navigable waters or in port, these wastes can be stored and taken care of by shore facilities. Work in the field has not gone much beyond making this a viable solution.

Solid wastes, as mentioned previously, are those wastes primarily solid in nature, consisting, as indicated by Table I, of paper products, cloth, rubber, food products, ceramics, metals and the like. These wastes are generated by a ship, as in a small floating city, because men work, eat, and live, and over a period of time generate solid wastes.

The first step in their analysis is to determine the amount of solid wastes generated by the ship. Since the shipboard solid waste problem has received little attention in the past, quantitative data are lacking. Most of the work in quantifying solid waste data has been sponsored by the U.S. Public Health Service in response to the Solid Waste Disposal Act of 1965, and deals with municipal and industrial wastes.

Quantitative data are necessary for this analysis, so it was necessary to approach the problem from three different directions in an effort to bracket the amounts generated. The objective of these approaches is not to achieve an exact, in-depth survey, but to obtain a reliable estimate of the quantities involved, in order to establish the magnitude of

the problem, and, if necessary, the size of a system for its disposal.

The first approach is to utilize Public Health Service figures and attempt to model the ship after them. The second approach analyzes the onboard storage capability of the ship, combines this with estimates of how much is used, and converts this to waste. The third approach is a survey of how much waste the ship generates in port, with an attempt to correlate this to the amount generated at sea. The combination of these approaches should realize a realistic and workable figure for shipboard solid wastes.

Combustion Engineering, Inc., of Windsor, Connecticut, carried out an in-depth study of solid wastes for the U.S. Public Health Service (2). In an analysis of approximately 600 cities, figures were developed for urban areas as well as for the United States as a whole.

	Solid Wastes (Urban) #/capita/day	Solid Wastes (U.S.) #/capita/day
Residential	2.4	2.4
Commercial	1.4	1.0
Bulky	0.3	0.3
Sub-total	4.1	3.7
Industrial	3.2	3.2
Total	7.3	6.9

The trend has been for these figures to increase with time. Solid waste generation per capita in the United States has doubled since 1920. Keeping this in mind, the model ship can be compared with the categories listed. The bulky and industrial waste categories are not generally applicable to

a ship of this type. Bulky wastes include such items as bundled newspapers and bagged leaves, which are not available to a ship at sea, and while repair ships and tenders have an industrial capability, the model ship performs work of this type only to the extent of her own maintenance and this work can be considered commercial in nature. The residential and commercial figures are applicable to the model ship. There are 150 men living in residence, as in a large apartment house, however their access to the outside world is much more limited than is the apartment dweller's, since only those items carried on board are available and deliveries or trips to stores are impossible. Therefore the residential figure for the ship should approach, but be somewhat less than the residential figure found by the Public Health Service.

On the commercial level, the ship must be self-sufficient and therefore possesses many of the commercial activities of a small town. Since the commercial figure decreases with decreased size and commercial activity from the municipal data, and the ship is small in this respect, and again due to lack of outside access, the ship's commercial figure should be much less than that found by the Public Health Service, especially at sea. The ship's commercial activity is also much greater in port than at sea. Using the 1966 United States figures, neglecting their time rate increase, and arbitrarily subtracting .4 #/capita/day from the residential figure due to lack of outside access, and halving the commercial figure due to lack of outside access

and size, a total of 2.5 #/man/day is arrived at for the ship. This amounts to 375 #/day or 5.85 tons* of solid wastes generated on a 35 day patrol. This is a sizeable amount.

As a check on the validity of the above model and the amounts arrived at, the onboard storage capacity may be investigated and coupled with consumption figures. The storage areas of the model ship may be broken down into two broad groups, food and non-food related. Using figures from (3), the ship has a storage capacity of nearly 40 tons for those materials likely to become solid wastes.

Food Storage	(tons)	Non-food Storage	(tons)
Commissary/Issue Room	7.8	Small Stores	1.8
Freezer	4.9	Ship's Store	4.5
Chiller	6.3	Bosuns Stores	2.2
Wardroom Stores	0.5	Flammable Stores	1.6
Total	19.5	General Stores	10.3
		Total	20.4

The food related stores are of the type that are nearly all consumed, but have a low percentage of waste. When embarking on a patrol, the food stores are full to capacity. Using a 90% consumption figure with 15% waste, food related wastes should be approximately 2.6 tons per patrol. This allows for four days excess food at the end of a patrol and considers that, in addition to the wrappings and containers, part of the food itself will be waste, as garbage.

The non-food stores do not have such a high consumption rate, but have a larger percentage of waste. Such things as rags and paper towels are 100% waste, when used. A 50% waste

*All references to tons denote long tons.

figure combined with a 30% consumption rate results in 3.1 tons of non-food related wastes per patrol, and a total of 5.7 tons of solid wastes per patrol.

The percentages of consumption and waste used in this section were viewed as fairly representative by members serving on ships of this type. The total arrived at supports the figure obtained earlier, however both methods may seem to be proving the addage that "liars can figure and figures can lie." These must be viewed as estimations and nothing more, however they do appear to be excellent avenues of approach for any future in-depth studies, and they do give a much firmer idea of the magnitude involved.

A much less arbitrary study was undertaken as the third method of determining the amount of solid wastes generated by the model ship. Beginning 3 February 1971, direct observation of the amount of waste generated in port was made for one week. The Boston Disposal Corporation has the contract for trash and garbage removal from the USCG Base in Boston. Unfortunately, this contract being for the entire base, no figures are kept on the ships separately, but the contract calls for daily pick-up, except Sunday, of a number of standard size containers. The containers serving the ship are of two sizes, five cubic yards and one cubic yard, and are placed on two piers, giving them a total waste capacity of 23 cubic yards. Pick-ups were made about 12:30 p.m. each day, so observations were made at noon, in order to estimate the amount present, and the containers were again examined after

pick-up. Interviews with the pick-up team and subsequent checks during the following week indicated that the results obtained were a good average. It should be pointed out that no attempt was made to allow for seasonal trends, if any.

During the period of this survey, five ships were using the pier facilities, the USCG high endurance cutters Hamilton, 378'; Sherman, 378'; Bibb, 327'; Castle Rock, 311' (for one day breasted to a third pier and not using the facilities under investigation); and the icebreaker Edisto. These all have similar crew size and facility for solid waste generation, and should not be greatly at variance with the model ship's figure.

Results of this survey, presented in Table II, show a rather uniform amount generated on a daily basis, and comparison between the two piers is quite good. The model ship generates nearly two and one-half cubic yards of solid waste per day. Using a conversion of 60 cu. yds. per 10,000 # solid waste (1), the ship generates 390 #/day or 6.1 tons over 35 days. These figures again support those arrived at previously, but a comparison of the ship's at sea and in port characteristics is necessary.

In port the ship does not support her whole crew as she does at sea. Some men are on leave, and liberty allows about three-quarters of the crew to leave the ship after working hours. However, access to the outside world is now easy, and the amount of onboard maintenance is much larger. Many items that the ship has ordered arrive, and

the containers and packing add to the waste. Therefore, the effect of smaller crew size is probably more than offset by being in port, and the at sea figure should be somewhat less than the in port figure.

The combination of the three methods shows good correlation, but an exact figure cannot be obtained, since the reliability of the methods employed is unknown. The intention was not to arrive at an exact figure in this study, but rather to get a good idea of the magnitude of the solid waste problem, and this we now have.

It is concluded that the 378' high endurance cutter generates 375 # of solid wastes per day at sea, and that on an average patrol would dump 5.85 tons of solid waste into the sea.

The results of the quantitative survey are summarized in Table II.

TABLE II

QUANTITATIVE SUMMARY OF MODEL SHIP'S SOLID WASTES

I. Municipal Model:

Waste Type	#/man/day
Residential	2.0
Commercial	0.5
Total	2.5

2.5 #/man/day (150 men) = 375 #/day

$$\frac{375\ \#/\text{day}\ (35\ \text{days})}{2240\ \#/\text{ton}} = 5.85\ \text{tons}$$

II. Storage Capacity Data:

Storage Type	tons	% waste	% consumption
Food Stores	19.5	0.15	0.90
Non-food Stores	20.4	0.50	0.30

19.5 tons (.15)(.9) + 20.4 tons (.5)(.3) = 5.7 tons

$$\frac{5.7\ \text{tons}\ (2240\ \#/\text{ton})}{35\ \text{days}} = 365\ \#/\text{day}$$

III. Inport Data:

Pier I

Day	Amount Present (cu.yds.)	Left from Previous Day (cu. yds.)	Net (cu.yds.)	No. of Ship-Days	Amt./Ship/Day (cu. yds.)
Monday*	13	7	6	6	1.0
Tuesday**	9	1	8	3	2.67
Wednesday	13	8	5	2	2.5
Thursday**	9	1	8	3	2.67
Friday	18	8	10	3	3.33
Saturday	9	1	8	3	2.67
-					
Total			45 /	20 =	2.25

*Sunday figures included in Monday.
**No pick-up on these days.

TABLE II (continued)

Pier II

Day	Amount Present (cu.yds.)	Left from Previous Day (cu. yds.)	Net (cu.yds.)	No. of Ship-Days	Amt./Ship/Day (cu. yds.)
Monday*	5	1	4	4	1.0
Tuesday**	7	1	6	2	3.0
Wednesday	13	6	7	2	3.5
Thursday**	6	1	5	2	2.5
Friday	11	5	6	2	3.0
Saturday	7	1	6	2	3.0
Total			34 /	14 =	2.43

Combined (Piers I and II):

$$\frac{(45 + 34) \text{ cu. yds.}}{(20 + 14) \text{ ship-days}} = 2.33 \text{ cu. yds./ship/day}$$

$$2.33 \text{ cu. yds./ship/day } (35 \text{ days}) = 81.5 \text{ cu. yds.}$$

$$\frac{81.5 \text{ cu. yds. } (10000\#)}{2240 \ \#/\text{ton} (60 \text{ cu.yds.})} = 6.1 \text{ tons}$$

$$\frac{6.1 \text{ tons } (2240 \ \#/\text{ton})}{35 \text{ days}} = 390 \ \#/\text{day}$$

IV. Overall Estimate:

375 #/day

5.85 tons for a 35 day patrol

The Refuse Act (U.S. Code 33) prohibits the dumping of solid wastes into the navigable waters of the United States, but at the present time ships are not prohibited from dumping them at sea. The quantitative analysis of the preceding section shows that a sizeable amount is dumped by one ship each year, since several patrols are made. When it is considered that many ships have a greater capacity than the model ship, and that thousands of ships are plying the seas, the result is hundreds of thousands of tons of solid wastes being dumped into the oceans each year.

Man relies on the land, the air, the seas or combinations of these to accept solid wastes, while maintaining the ecological balance. Pollution results when these wastes are discharged in such a manner or at such a rate that there is an inability to maintain this balance. In view of the large amounts generated, and since these amounts will increase in the future, as will the stringency of anti-pollution laws, a ship of this type may require some onboard processing capability.

An onboard disposal system is also attractive from the standpoint of extended operations in the navigable waters and reduced service requirements in port. Onboard storage, odor, and cleanliness problems could be greatly reduced and shore facilities relieved of much of their storage and pick-up responsibilities.

Therefore, the pollution control system for the 378' high endurance cutter will be designed to have some onboard

disposal capability.

METHODS OF SOLID WASTE DISPOSAL

Having decided not to discharge totally unprocessed solid wastes into the sea, methods of disposal must be investigated to see which are applicable to the problem, and determine the qualities of those that are, so that a systems study may determine the best from among them.

A. Landfill and Open Dumping

The most common method of solid waste disposal in the United States, today, is landfill and open dumping. This type of disposal, as the names indicate, is the present method of shipboard waste disposal at sea, using the oceans as the dump or fill area. While this method of disposal may be very useful on land, it cannot be used in navigable waters, and is unattractive without any prior processing even at sea. Its only application would be as a secondary method at sea.

B. Incineration

This method presents a very attractive method of solid waste disposal, since the majority of solid wastes are combustible. The process is used in many apartment houses with demands similar to that of the model ship. The volume of solid wastes can be reduced to 10%, and the weight to 25%. A sterile residue is produced consisting of metals, ceramics and other non-combustibles or combustibles not fully burned.

Estimates are that, with proper design, an incinerator could reduce volume to 5% (2). On a typical patrol, 82 cu. yds. of refuse could be reduced to about 8 cu. yds. or less, with a weight reduction from 6.1 tons to about 1.5 tons. The process does involve burning, and therefore runs the risk of causing air pollution, since we are converting our solid wastes and discharging them into the air. Present incinerators can, however, be made to meet all present air pollution requirements with proper equipment. Such equipment would be required for this system. The residue could possibly be dumped at sea, but could be held and offloaded in port. The cost of incinerators is $3000-$4000 per ton of rated daily capacity (2). Incineration also has possible application to both the sewage and ballast/bilge wastes. In addition, waste heat recovery methods might be tied in with incineration to make some economic gain from the wastes. Refuse has an average lower heating value of 4,500 BTU/# (2), and the heat exhausted from this process could be used to heat feed water for boilers or evaporators.

C. Size Reduction and Densification

Processes of this type also present attractive methods for shipboard waste disposal. Grinders and shredders are often used prior to other methods of disposal, but discharges directly from these machines could not be made in the navigable waters or in port. They do have possibilities at sea, as well as being a preparation for further processing.

Compaction is another method presently used in apartment houses with success. Waste volume can be reduced to about one-third, but the weight is not reduced, since the refuse is merely made more dense. Compacted wastes can be packaged to make them sanitary. On an average patrol, 82 cu. yds. could be reduced to 27 cu. yds. In the navigable waters and in port, storage would be reduced considerably, but at sea, reduction of 10 to 1 would be required. A lesser reduction would allow the refuse to float in a less acceptible condition than if dumped as it is presently. Costs for machines with quarter to half ton per day capacity are $3000-$4500. Some of the disadvantages of these machines, such as the requirements for high pressure air and a critical dependence on electrical energy are not so detrimental on board a ship, where these items are more readily available. However, packaging and odor problems as well as possible fire and health hazards do exist. The return of solid wastes to port does leave the possibility of reusing them, an idea which is gaining much acclaim today.

D. Composting

Composting is a process, involving aerobic decomposition or fermentaion of organic material, which finds its greatest application in Europe. There are a variety of methods available to accomplish this process, all of which involve time, and proper temperature conditions. Not all materials, metals and glass, for example, can be converted to compost. The process requires excessive equipment and

storage area from a shipboard standpoint, and while composting can be more economical than incineration on a 100 ton/day basis, the amount generated by the model ship is so small that the process would be quite expensive. Some size reduction results from the overall process, but it is mostly a conversion from one waste product into another, requiring space that is not available on a ship at sea. Therefore, composting is not regarded as applicable to the shipboard solid waste problem as a primary system, though it has been well studied for the sewage waste systems.

E. Chemical Processing

Many chemical processes are available for use on solid wastes. Hydrolysis, Extraction, Pyrolysis, Carbonization, and Evaporation are only a few. These processes are primarily intended for the recovery of usable materials and in practice are generally costly. An excellent discussion of twenty-nine processes is found in (4). The only generally attractive methods are those involving burning, which already have been considered under incineration, so none of these methods will be considered as applicable to solid waste problem.

F. Separation Techniques

Processes of this type, while not actually methods of disposal, are usually incidental to the overall process. Sorting, by mechanical, electrostatic, gravity, or hand methods, can be very useful in separating desirable items from the rest, and will be considered as a secondary method for

solid waste disposal.

Table III presents a summary of the solid waste disposal methods and their applicability to the shipboard problem.

TABLE III

SUMMARY OF SOLID WASTE DISPOSAL METHODS

Methods	Primary*	Secondary*	Comment
Landfill/Open Dumping	No	Yes	At sea only
Incineration	Yes	Yes	Attractive
Size Reduction Grinders/Shredders	No	Yes	Increase primary efficiency
Densification Compactors	Yes	Yes	Attractive
Composting	No	Possible	Sewage treatment possibilities
Chemical Hydrolysis Combustion (see Incineration) Extraction Pyrolysis Carbonization Cxidation Sintering Precipitation Calcination Melting Electrolysis Evaporation Ion Exchange Miscellaneous (4)	No	No	High cost; applications too specific
Separation Hand Gravity Mechanical Electrical	No	Yes	Increase primary efficiency

*Primary systems are those which can accomplish the disposal principally by themselves. Secondary systems require a large degree of help from other systems in order to be successful.

THE SHIPBOARD SEWAGE WASTE PROBLEM

The analysis of this problem is several steps ahead of that for shipboard solid wastes. Several federal agencies have done work in this field, including the U.S. Navy, which has conducted a survey to determine the quantities and properties of shipboard sewage wastes. Research, development and testing of sewage treatment systems for both large and small ships have also been carried out. Present systems are by no means cure-alls, but in general, the needs in this area seem to be better established than in the others considered in this thesis.

Until recently, the method of shipboard sewage waste disposal has been direct overboard discharge, both in port and at sea. This practice has led to unsightly floating solids, marred natural beauty and impaired recreational value. In addition, it has proved hazardous to human health, animal life and plant life. This is especially true in restricted waters, which are unable to accept these untreated wastes as readily, without altering the natural environment. Human wastes may contain dangerous concentrations of pathogenic organisms causing disease. Their decomposition in water degrades the dissolved oxygen level and they are rich in nitrogen and phosphorous nutrients promoting the growth of algae and surface scums (12).

Sewage wastes from ships are made up almost entirely of water, with only about 1% of the discharge being contaminants. A summary of the properties of shipboard sewage wastes and

definitions of unfamiliar terms are presented in Table IV.

The quantitative data of Jakobson and Posner (13) present a maximum flow figure of 34 gallons/man/day for naval ships. This survey, however, includes only water closets and urinals. When the other systems listed in Table I are included, the flow figure may rise to as much as 150 gallons/man/day (1). These other systems do not present much of a hazard under normal conditions, and are not generally considered to require treatment. Using an average flow of 30 gallons/man/day (1), the model ship pumps about 4500 gallons of sewage wastes, requiring treatment, over the side each day. Of this amount, 0.2 #/man/day or 30 #/day are entrained sewage solids (14).

The crux of the sewage waste problem, then, is that the liquid volume involved is very large, even though the amount of contaminant is not. These large volumes preclude storage on board for any length of time, thus necessitating overboard discharge. This in turn creates the sewage waste pollution problem.

A summary of the quantitative data on shipboard sewage wastes is also presented in Table IV.

TABLE IV

SUMMARY OF DATA ON SEWAGE WASTES (13)

Suspended Solids, ppm avg.	236
Biochemical Oxygen Demand (BOD), ppm avg.	102
Coliform Density Index, MPN/100 ml, geometric avg.	4.8×10^5
Settleable Solids, ppm avg.	5.4
Volatile and Organic Solids, ppm avg.	5,825
Total Solids, ppm avg.	33,000
Nitrogen, Total, ppm avg.	127.3
Dissolved Oxygen, ppm avg.	5.38
pH, avg.	7.38
Per Capita Flow, GPD max.	34.0
Per Capita Flow, GPD min.	22.6
Per Capita Flow, GPD avg.	26.2
Per Capita Sewage Solids, #/man/day avg. (14)	0.2

DEFINITIONS OF UNFAMILIAR TERMS (16)

1.	Aerobic Organism	An organism living or active in the presence of oxygen.
2.	Biochemical Oxygen Demand	The oxygen required during the stabilization of the decomposable bacteria matter of aerobic bacterial action.
3.	Suspended Solids	Solids in which suspension occurs in the settling tank.
4.	Coliform	A group of bacteria inhabiting the intestines. Contains pathogenic colonies which can cause disease.
5.	Comminuter	A chopper, grinder or macerator of raw sewage.

No laws presently govern the discharge of sewage wastes on the high seas, however many federal and state laws prohibit the discharge of raw sewage into the navigable waters of the United States. Water pollution of this nature has been one of the objects of major, recent Congressional legislation, including the Federal Water Pollution Act, in 1956, which required states to establish standards for interstate and coastal waters. This was amended by the Water Quality Act of 1965, establishing the Federal Water Pollution Control Administration, and by the Clean Water Restoration Act of 1966, calling for a report on water pollution due to vessels in the navigable waters (15). Executive Orders have called on federal agencies to provide leadership and meet the most stringent requirements in this area. Toward this end, the Navy has established a pollution control laboratory at their Research and Development Center, and launched a broad program to control the wastes discharged by ships (16). The Coast Guard, in cooperation with the Federal Water Pollution Control Administration, has also carried out testing of units on board its vessels. The Public Health Service, the Corps of Engineers, the U.S. Coast Guard and the Geodetic Survey, and the Maritime Administration have all initiated programs in this area (12).

Water quality standards are presently set by each state, subject to federal approval. This has resulted in non-uniformity, and in fact many states have no water quality regulations with regard to ships. Proposed amendments to the

interstate quarantine regulations and standards set forth by the U.S. Public Health Service require 50 ppm of BOD, 150 ppm or less of suspended solids, and a coliform MPN of 1000 or less per 100 milliliters (12,16). These are also compatible with Canadian standards, however requirements for some individual states, the Great Lakes, and some foreign countries are more severe. An upgrading of federal standards to 50 ppm of BOD, 80 ppm of suspended solids, and a coliform MPN of 240 or less per 100 ml. appears to be the future trend.

Comparison of these values with the shipboard sewage figures shows that treatment is necessary in order to meet these requirements, when in the navigable waters or in port.

It is estimated that the model ship will be required to have treatment capability by 1975. Therefore, a capability of meeting the present Public Health Service standards will be incorporated in the pollution control system for this ship.

METHODS OF SEWAGE WASTE DISPOSAL

The legal, quantitative, and qualitative aspects of the sewage disposal problem all require some method of treatment. This has been recognized by the federal agencies and industry, and a variety of sewage waste treatment techniques have shown potential as acceptable systems.

A. Biological/Extended Aeration

Biological systems, of which the extended aeration activated sludge process is the most attractive, utilize

bacterial digestion by which organic matter is converted to a more stable organic form. A typical system would consist of a comminutor, a blower, and an aeration and settling compartments (17). Coarse materials are screened out, organic solids ground into small particles, sewage aerated, sludge settled and returned to the aeration chamber, and the liquid chlorinated before discharge (12). Of ten proposals submitted by industry to the Naval Ship Systems Command, four were biological in nature. All sewage can be adequately treated by this method; however, the extended processing time requires a large, heavy unit making the process applicable only to larger ships. A U.S. Navy study reports that a system of this type, serving a guided missile frigate with a crew of 330 men, would weigh 30 tons and take up 550 square feet of deck space (16).

B. <u>Incineration/Mechanical</u>, <u>Electro-Chemical</u>

Incinerators may be used to destroy human body wastes. These wastes, collected in an incineration cup, may be burned by heat developed from electricity, fuel oil or liquefied petroleum gas. Incineration offers a lightweight process requiring minimal space, which prevents pollution from human body wastes, but does not effectively treat the waste waters, and may present an increased fire hazard (12, 18).

For more complete treatment, combinations of mechanical, electro-chemical devices may be used with the incineration process. Six of the 10 industrial proposals, mentioned earlier, were of this type. Removal of the solids from the

liquid by filtration, straining or floculation techniques is the first step, after which the solids are treated by thermal destruction techniques, and the liquids by adsorption, floculation, aeration and chemical processes. The final step, prior to discharge, is disinfection. A typical system utilizes a solids interceptor, incinerator, holding tank, and chloro-flotator. An experimental unit of this type has been delivered to the Navy by Colt Industries' Fairbanks Morse Research Center for service evaluation (19). The unit has a capacity for 175 men and appears to meet the Public Health Service requirements. For the guided missile frigate mentioned previously, this system would weigh 7.6 tons and take up 77.4 square feet in deck area, a considerable savings (16).

C. Macerator-Disinfectors

Processes of this type cut up the solids into small pieces in a macerator and treat the sewage mixture with a disinfectant, usually chlorine. Units of this type are small and lightweight, and evaluation by the Navy (21) concludes that this system is satisfactory on small ships. Testing has also been done by the Coast Guard, and other federal agencies have installed units of this type on their vessels. A typical unit consists of a macerator, holding tank, and disinfectant injection system (22). The quality of treatment by this process is highly suspect. BOD and suspended solids are hardly affected and it is doubtful that these units can meet the Public Health Service requirements (12). Therefore

its application to ships will be quite limited.

D. Holding Tank/Recirculating

The use of a holding tank for sewage wastes presents a solution, when shore facilities are available to take care of them. As mentioned earlier, the large volume involved requires extensive storage space, when in port for any length of time. Also, not all ports of call have these facilities. This is not considered acceptable for the model vessel.

A substantial reduction in the volume of sewage wastes can be made, if a recirculating system similar to that used in aircraft is employed. A plant of this type, described by (23), sterilizes, deodorizes, decolorizes and liquefies human wastes and reuses the "resultant liquor" for flushing water closets, thus eliminating additional use of sea water. The main components of this process are a pressure breakdown tank, comminutor, chemical and settling tanks, pressurized storage tank, and a recirculating system. The amount of storage may be reduced to less than 5% of the normal volume of sewage. For the model ship this would be about 200 gallons/day. This process appears most feasible for ships with short turn around time. A zero pollution level is met in port and the held sewage discharged at sea. The in port time for the model vessel is such that this method would probably not reduce the volume sufficiently to make it applicable. Psychological problems might also be encountered in reusing waste water, and the discharge, at sea, of several days wastes would be quite potent.

A comparison of sewage waste treatment processes, with comments on their range of applicability, is presented in Table V.

TABLE V

SUMMARY OF SEWAGE WASTE DISPOSAL METHODS

Method	Primary	Secondary	Comment
Biological	Yes	Yes	Large size and weight restricts it to large vessels having adequate space; quality of treatment is excellent
Incineration/ Mechanical, Electro-Chemical	Yes	Yes	System similar to Colt provides adequate quality of treatment and requires minimal space and weight; medium and large ships
Macerator-Disinfector	No	Yes	Restricted to use on small vessels; has questionable treatment quality
Holding Tank/ Recirculating	Possible	Yes	Provides adequate method for oceangoing ships having short times in port, and those vessels ensured of shore disposal facilities at all ports of call

THE BALLAST, BILGE, AND MACHINERY WASTE PROBLEM

Oil pollution, which is the heart of this problem, has undoubtedly received the most publicity of any of the areas discussed. The oil pollution problem posed by ships, other than that resulting from unforeseen damage such as collision, is due to the discharge of oily water into the sea. This oily water comes from three main sources on the model ship: that which results from ballasting empty fuel tanks, that which collects in the bilges, and that which is discharged after use by machinery.

Ballasting is a normal procedure for ships at sea for any length of time. In order to maintain proper stability, sea water is taken on to compensate for emptied fuel tanks. Performance is also enhanced by maintaining such things as proper propeller immersion. Vessels not afforded with the luxury of separate fuel and ballast tanks mix the incoming sea water with any fuel remaining in the tanks. Tank design can minimize this, but there must be a space between the suction piping and the tank bottom. Therefore, suction is lost at this point, and due to rolling in a seaway probably earlier. Estimates are that 0.35% of the oil remains in a tank (26). Before the ship refuels, she must dump this oily water overboard. In the case of the model ship, which burns about 2000 gallons of No. 2 diesel oil per day, some 70,000 gallons are expended on a patrol. Of these, she is required to ballast approximately 51,000 gallons (3). Therefore, when deballasting, she discharges about 180 gallons of oil into the

sea.

The bilge water problem is a more continuous one, of smaller total magnitude, but present at all times, in port or at sea. Bilge water collects due to leakage, condensation, and seepage and may contain lubricating oils and grease as well as fuel oil. The level of accumulating water in the bilges must be kept down either by pumping it overboard or to a separate collection tank. The necessary volume of such a tank for the model ship would make it impractical. The amount of bilge water accumulating varies widely from ship to ship. Unfortunately, no exact data was obtained for the model ship, but estimates place the amount at less than 500 GPD.

Machinery discharges from evaporators or cooling water systems do not generally present a problem from a pollution standpoint. With proper design and maintenance, these systems should normally require no special treatment other than monitoring. Oil may leak into cooling water systems which employ direct cooling of oil by sea water. However, when this is detected, the system may be shut down for repair or, if necessary, run under emergent conditions, which is permissible. In many installations, the salt water is separated from the oil by an on board fresh water recirculating system, which eliminates the problem for all practical purposes. The machinery discharges of the model ship are not felt to require any further consideration.

A summary of the results of a Ballast Survey taken by the USCGC Chase is presented in Table VI.

TABLE VI

BALLAST SURVEY FROM USCGC CHASE*

Tank	Capacity (gallons)	Required to ballast (3)	Estimate of oil remaining (gallons)
4-256-1-F	9806	No	-
4-256-2-F	9378	No	-
5-168-1-F	11321	Yes	40
5-168-2-F	11321	Yes	40
5-120-0-F	29307	Yes	100
Normal condition at end of 35 day patrol. Total			180 gallons
5- 80-0-F	5784	No	-
4- 88-3-F	2311	Yes	-
4- 88-4-F	2311	Yes	-
5-104-0-F	22560	Yes	-
5-144-1-F	16498	Yes	-
5-144-2-F	15753	Yes	-
5-120-1-F	9853	Yes	-
5-120-2-F	9853	Yes	-
Minimum Operating Condition.			
5- 96-1-F	8120	Yes	-
5- 96-2-F	8120	Yes	-
3-328-1-F	7118	Yes	-
3-328-2-F	7118	Yes	-
3-256-0-F	27458	No	-

*Patrol from 1 February to 6 March 1971.

Legislation intended to reduce oil pollution has been in existence in this country since the Oil Pollution Act of 1924 prohibited the discharge of oil into the coastal navigable waters, except under emergent conditions. The Federal Water Pollution Control Act, the Water Quality Act of 1965, and the Clean Water Restoration Act of 1966, mentioned in the sewage waste section, are aimed at control of oil pollution as well. This problem has also become the object of international concern. The International Convention of the Pollution of the Sea by Oil, 1954, and amended in 1962, has been accepted by 42 countries. The United States adopted the Convention in 1961, with reservations about territorial waters, and implemented its ideas in the Oil Pollution Act of 1961. The Convention prohibited the discharge of persistent oils, such as crude, fuel, heavy diesel, and lubricating oils, from selected zones, generally 50-100 miles from land. In addition, the standard by which pollution could legally be measured was established and defined as an oily mixture having an oil content of 100 parts or more in 1,000,000 parts of mixture (100 ppm).

Applying this standard to the model ship, the oil discharged from ballast alone would be reduced to 5 gallons or less. A zero pollution level is ultimately desired, but present technology can achieve this only by offloading in port, a solution having many drawbacks and precluding an investigation of shipboard systems. Therefore, the 100 ppm standard will be applied as that which the model ship's

pollution control system should meet.

METHODS OF OILY WASTE DISPOSAL

In order to meet the present legal requirements, the model ship requires a method of disposing of its oily wastes. The solution is to retain the oil on board and discharge the water, but, due to the large water content and the mixing action of ship motion, the separation of these two liquids is a difficult problem. Most of the world's commercial fleet has adopted a "load-on-top" technique (27) to reduce the amount of oil dumped at sea. This, coupled with other methods, might meet the present standards. These other methods are separation techniques aimed at removing the oil from the water. A discussion of the state-of-the-art of such techniques, and methods of measuring performance is presented in (28).

A. "Load-on-Top"

This procedure consolidates the oil from tank washings and ballasted tanks by pumping it to a slop tank after it has settled. This process alone would not meet present standards, but it may be aided by heating or demulsifiers. The Soviet Union, combining this method with the use of special cleaning agents that aid in separating out the oil, claims to be able to meet the 100 ppm standard (30). As presently practiced, this procedure would introduce a degree of complexity to the deballasting process. This is not considered desirable for a ship having such a small oil

dumping capacity. The accumulation of bilge water and tank washings would also require a large storage volume. Due to its dependence on other techniques, "load-on-top" is not considered to be a primary method of disposal, but the use of a slop tank for dirty oil is a desirable secondary feature.

B. Settling

Oil and water are immiscible liquids, in that they do not mix or blend. By allowing the oil-water mixture to stand for a period of time, the oil will float to the top, since it is less dense. This may be aided by heating. Settling takes place in the ship's ballast tanks naturally, but the ship's motion tends to cause the layers to be less well defined and is detrimental to separation. Smaller, baffled tanks may minimize this, and, in fact, the model ship presently employs a device of this type for its bilge water. The main drawback of this process is that it is very slow. The present ship's bilge water settler has a capacity of only 20 gallons/minute. It is approximately 2½ feet in diameter, 6 feet high, weighs 300 # dry, and holds 260 gallons. This works out to a holding time of 13 minutes. Scaled up to a rate of 600 gallons/minute, a settler of over 1000 cubic feet would be required for de-ballasting.

C. Flotation

This technique is similar to settling, but employs an insoluble gas, such as air, to surround and float suspended drops of oil at a faster rate, by increasing the density

difference between the oil drop and the water. Air-oil vapors may form explosive mixtures, however, so this process may present a severe hazard. This process is still a slow one. An investigation (34) of devices of this type found a required holding time of 13 minutes, which is the same as that of the bilge water settler discussed previously. A source of compressed air or gas would also be required.

D. <u>Centrifuge</u>

Centrifuges remove liquids and/or solids from other liquids by use of centrifugal force, developed by the motion of its core, instead of gravity. These devices are used on many ships to separate water from oil, but the reverse process is much more difficult. The small density differences require large centrifugal force for separation, and the large capacity necessary results in heavy, high powered units. The process also becomes inefficient and uneconomical, when the percentage of water in the mixture is large. Therefore, centrifuges are not considered applicable as primary ballast or bilge water separators (28).

E. <u>Hydrocyclone</u>

This device is similar to the centrifuge, but the liquid is pumped in and forced into a circular motion by tangential injection against the circular configuration of the hydrocyclone. The advantage of the hydrocyclone over the centrifuge is that there are no moving parts, thus reducing cost and maintenance. However, turbulence reduces efficiency,

and considerable pumping power is required. Thus far, only low flow rates have been achieved and it appears that several hydrocyclones in battery would be necessary to meet the quality requirements. Due to their present state-of-the-art, hydrocyclones are also considered inapplicable as primary ballast or bilge water separators.

F. Coalescer/Filter

Devices of this type attempt to separate liquids by lowering interfacial tension. Woven meshes, screens or mats may be used to physically break interfacial films. The principal problem has been clogging, but recent tests for the U.S. Maritime Administration (34) have shown that deballasting rates of 600 gallons/minute are achievable for oily water in the quality range required. While development is not yet complete, it is felt that a weight of 8 tons wet, a volume of 200 cubic feet, a flow rate of 20 gallons/square foot, and a quality of 20 ppm are achievable. With no moving parts, these devices are reliable and have low maintenance requirements. The model ship presently uses units of this type for the reverse process of purifying diesel oil and JP-5 successfully.

G. Other Methods

Evaporation/Distillation, Freezing, Selective Adsorption, Chromatographic, Sonic, and Electric/Magnetic separation techniques do not show much promise as primary methods. Most are in the early development stages. The use of Membranes is attractive, but again needs a great deal of research and

development. The use of Chemicals as demulsifying agents may be helpful, but adds another pollutant to the problem and may present other hazards. Finally, Biological techniques do not appear to be favorable. None of the methods in this section are considered to be primary methods of disposing of oily wastes.

A summary of the methods of disposing of shipboard oily wastes is presented in Table VII.

TABLE VII

SUMMARY OF OILY WASTE DISPOSAL METHODS (28)

Techniques	Primary	Secondary	Comment
"Load-on-top"	No	Yes	Dirty oil tank necessary
Settling	Yes	Yes	Slow process
Flotation	Yes	Yes	Auxiliary process only; possibly hazardous
Centrifuge	No	Yes	Also suitable for removing water in oil
Hydrocyclone	No	Yes	Needs further development
Coalescer/Filter	Yes	Yes	A completely satisfactory element yet to be found
Evaporation/ Distillation	No	Possible	High cost
Freezing	No	Possible	High cost
Selective adsorption	No	Possible	Slow process; disposal of adsorbents needs to be considered
Chromatography	No	Possible	High cost and low rates
Sonic	No	Possible	May break emulsions or cause emulsion shattering of coalesced globules
Membrane	No	Yes	No satisfactory membrane yet; slow process
Electric/Magnetic	No	Possible	Needs development
Chemical	No	Occasional limited use of demulsifying agent	Requires new system equipment and trained operator; may produce another pollutant
Biological	No	No	May act on new fuel charged unless thoroughly cleaned out from tank; may present problems for personnel

EXTENT OF SYSTEM CAPABILITY

Thus far, the investigation of the pollution control problem has shown that some means of disposal is necessary in each of the areas discussed. These means may be provided by the ship itself, by shore facilities or even by another ship. Prior to the selection of a shipboard system, therefore, it is necessary to decide on the extent of the disposal capability to be built into the model ship.

An investigation of this nature has been carried out in (35). In this study, a systems analysis was applied to several concepts of shipboard waste disposal, each giving the ship a certain level of capability. These concepts included: "total" on board processing, "no" on board processing, and three intermediate degrees of processing. In all but the "total" mode, shore facilities or fleet pollution control vessels were necessary for final disposal. The results of the study indicated that the "total" on board capability was best for both new construction and existing vessels requiring a back fitting of equipment. The results seem logical, since the ship would be cleaning up its own mess, but other important factors also warrant discussion. The dependence of a ship on certain required shore facilities can be highly restrictive. It seems unlikely that, with no legislative pressure, many ports of call would provide the necessary support, especially foreign ports, which the model and most oceangoing vessels are likely to visit. Reliance on shore facilities also places a large burden on the municipal areas.

Discharge of sewage wastes into already overloaded municipal sewers and solid wastes, when landfill for most urban areas is rapidly becoming less available, are two examples.

Older ships must be treated somewhat differently. For ships with only a few years of service left in their life cycle, an elaborate system of disposal would be exceptionally costly and unnecessary. For those ships, maximum advantage of existing facilities should be taken to ensure adequate disposal. The system to be designed in this thesis will be for new ships and will provide these ships with a total on board processing capability.

A summary of the analysis carried out in (35) is presented in Table VIII.

TABLE VIII

ANALYSIS OF EXTENT OF SYSTEM CAPABILITY (35)

Marks range from 1 to 10; a high mark indicates a relatively important item or a relative desirability of one concept over another.

Item	Relative Importance	Total onboard New	Total onboard Bkfit	Partial onboard New	Partial onboard Bkfit	No onboard
Wt. req'd. on user[1]	9	7	7	10	10	2
Vol. req'd. on user	10	3	3	10	10	2
Effectiveness[2]	8	10	10	3	3	0
Loss of capability[3]	10	10	5	10	6	1
Effect on fleet	10	10	10	0	0	0
Backfit cost	1	10	3	10	7	3
Transfer sys. cost	4	10	10	5	5	2
FLTPOC cost[4]	6	10	10	2	2	2
Total		483	423	356	313	67

Conclusions: In both cases (backfit on existing ships and designing into new ships), the total onboard processing system is best.

Notes: 1. Marks given inversely proportional to weight and volume required.

2. The ability of the system to fulfill the design requirements.

3. Equipment which would have to be removed for weight, moment, and volume compensation.

4. Costs to include annual operating costs and crew requirements of fleet pollution control (FLTPOC) equipment.

SYSTEM SALIENT FEATURES

Before selecting the pollution control system components, it is necessary to develop the characteristics on which they are to be judged.

The characteristics selected for this analysis are those used for the U.S. Navy in a waste disposal study. A more detailed discussion may be found in Appendix B of (25). These characteristics are those concerned with vessel performance, and are weighted by their relative importance. By numerically rating each characteristic, a performance score is arrived at for each component. Ten basic breakdowns were used:

A. Safety

This factor considers fire and explosion hazards and hazards to personnel from chemicals and the like. It is weighted 17 out of 100.

B. Reliability and Maintainability

This concerns the complexity and accessibility of the system, the skills required for maintenance, and the likelihood of availability. It is weighted 15 out of 100.

C. Operability

This involves ease of automation, skills and personnel required to operate, and usage. This is weighted 13 out of 100.

D. <u>Habitability</u>

Habitability includes cleanliness of the system and the odors evolved. It is also weighted 13 out of 100.

E. <u>Ship Operating Procedures</u>

This item considers the ship's ability to operate normally for extended periods in inland waters, in port, and entering or leaving port. It is weighted 15 out of 100.

F. <u>Deck Area Required</u>

This includes space for all components and holding tanks required by the system, which might otherwise be used. It is weighted 5 out of 100.

G. <u>System Weight</u>

As with space, a net weight is added to the vessel by carrying the system. For ships already in service, a backfit might require a sacrifice of present capability in order to afford the system. A weight of 4 out of 100 is applied here.

H. <u>Flexibility for Upgrading</u>

This involves the ability of the system to meet more stringent quality requirements in the future. It is weighted 6 out of 100.

I. <u>Development Risk</u>

This factor concerns the likelihood of developing a workable component or system in time to meet the quality requirements. It is weighted 5 out of 100.

J. <u>Flexibility for Use in Foreign Ports</u>

International relations may be affected by the inability of a system to operate without shore support. This factor is weighted 7 out of 100.

These ten characteristics were developed by two sets of evaluators in the study mentioned previously. These two groups represented the designer and the operator. The weighting factors used here are the average of the factors applied by these two groups.

In rating the performance of the system components, a five value scale will be used from very good to very poor. This was suggested over a three value scale to offset the tendency to rate in the average category.

A summary of the salient system features, their weighting factors, and the numerical rating system is presented in Table IX.

TABLE IX

SUMMARY OF SYSTEM SALIENT FEATURES,

WEIGHTING FACTORS, AND NUMERICAL RATINGS (25)

Primary Characteristics	First Set of Values	Second Set of Values	Overall Average
Safety (S)*	0.21	0.12	0.17
Reliability and Maintainability (R/M)	0.15	0.14	0.15
Operability (O)	0.14	0.12	0.13
Habitability (H)	0.15	0.11	0.13
Ship Operating Procedures (SOP)	0.13	0.18	0.15
Deck Area Required (A)	0.04	0.08	0.05
System Weight (W)	0.02	0.07	0.04
Flexibility for Upgrading (FU)	0.06	0.06	0.06
Development Risk (DR)	0.04	0.05	0.05
Flexibility for Use in Foreign Ports (F)	0.06	0.07	0.07
Totals	1.00	1.00	1.00

	Numerical Value
Very Good	5
Good	4
Average	3
Poor	2
Very Poor	1

*Letters in parentheses are abbreviations which will be used in future reference to the primary characteristics.

SYSTEM SELECTION

Since there are many available methods of disposal in each of the areas, a fatal flaw procedure will be used first to bring the analysis down to a more workable level. Next the system will be suboptimized by choosing the most attractive method of disposal for each of the separate areas. Finally, overlap of the areas and the methods of disposal will be investigated to determine if the chosen system can be improved by a combination of the areas and/or the methods of disposal.

The following methods of disposal are considered to have fatal flaws that make them unacceptible as primary methods of disposal, within the assumptions of this thesis: Sanitary Landfill and Open Dumping, Composting, Chemical Processing, and Separation of Solid Wastes; Maceration-Disinfection of Sewage Wastes; and "Load-on-Top", Centrifuge, Hydrocyclone, Evaporation/Distillation, Freezing, Selective Adsorption, Chromatographic, Sonic, Membrane, Electric/Magnetic, Chemical, and Biological Methods of Oily Waste Disposal.

The elimination of these processes still leaves a variety of available methods of disposal in each area. These methods will now be investigated area by area, rating each on the primary characteristics numerically as described in the previous section. The numerical rating values are arbitrary and are for comparative purposes in each area only. No attempt should be made to correlate values between areas.

A. Solid Wastes

Factor	(Weight)	Size Reduction/Densification Rating	Score	Incineration Rating	Score
S	(0.17)	3	0.51	3	0.51
R/M	(0.15)	3	0.45	3	0.45
O	(0.13)	3	0.39	3	0.39
H	(0.13)	3	0.39	4	0.52
SOP	(0.15)	3	0.45	4	0.60
A	(0.05)	3	0.15	4	0.20
W	(0.04)	3	0.12	4	0.16
FU	(0.06)	2	0.12	3	0.18
DR	(0.05)	3	0.15	3	0.15
F	(0.07)	2	0.14	4	0.28
Total	(1.00)	-	2.87	-	3.44

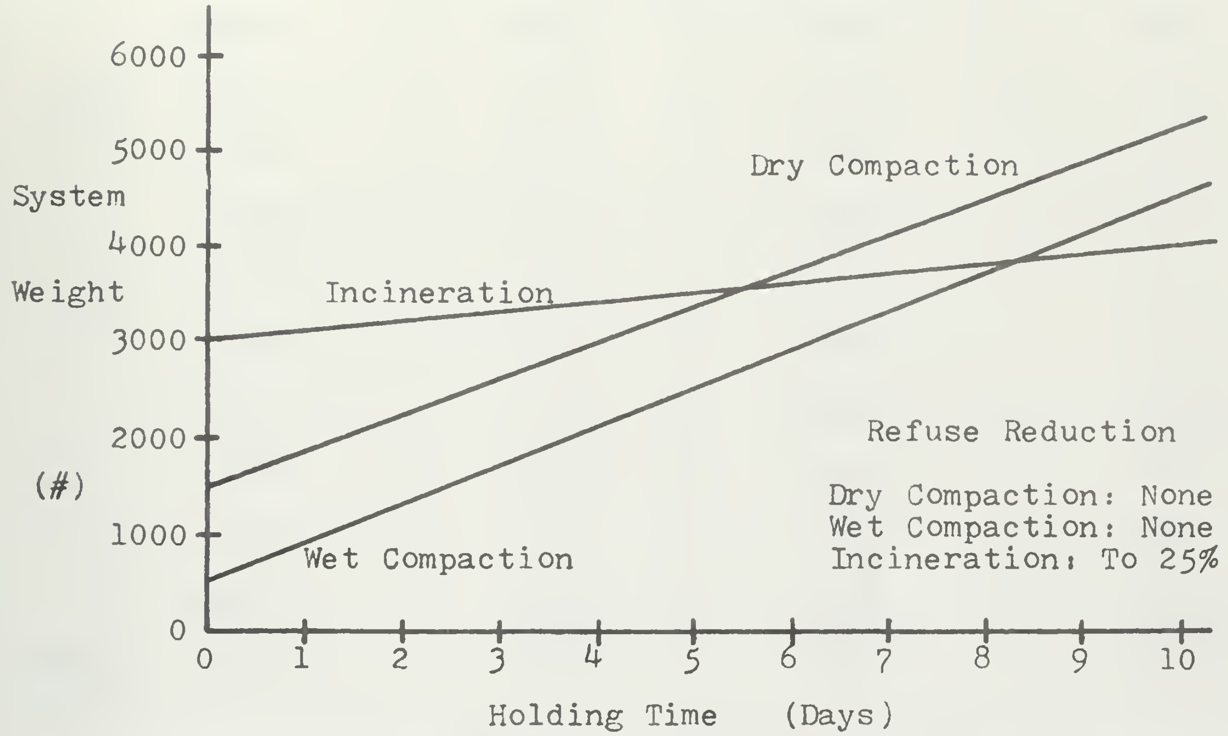
Methods considered in this analysis were grinding, wet and dry compaction with reduction ratios of up to 6 to 1, and incineration. Information on the ability of each of these methods came primarily from (2, 4, 6, and 11). Much of this information is qualitative in nature. Quantitative relationships between methods for System Weight and Deck Area Required are shown in Figure 1. These are based on an original system weight and area plus an accumulated weight and area for stored wastes of 100 #/day and 0.85 square feet/day for incineration, 375 #/day and 2.8 square feet/day for dry compaction, and 400 #/day and 1.7 square feet/day for wet compaction.

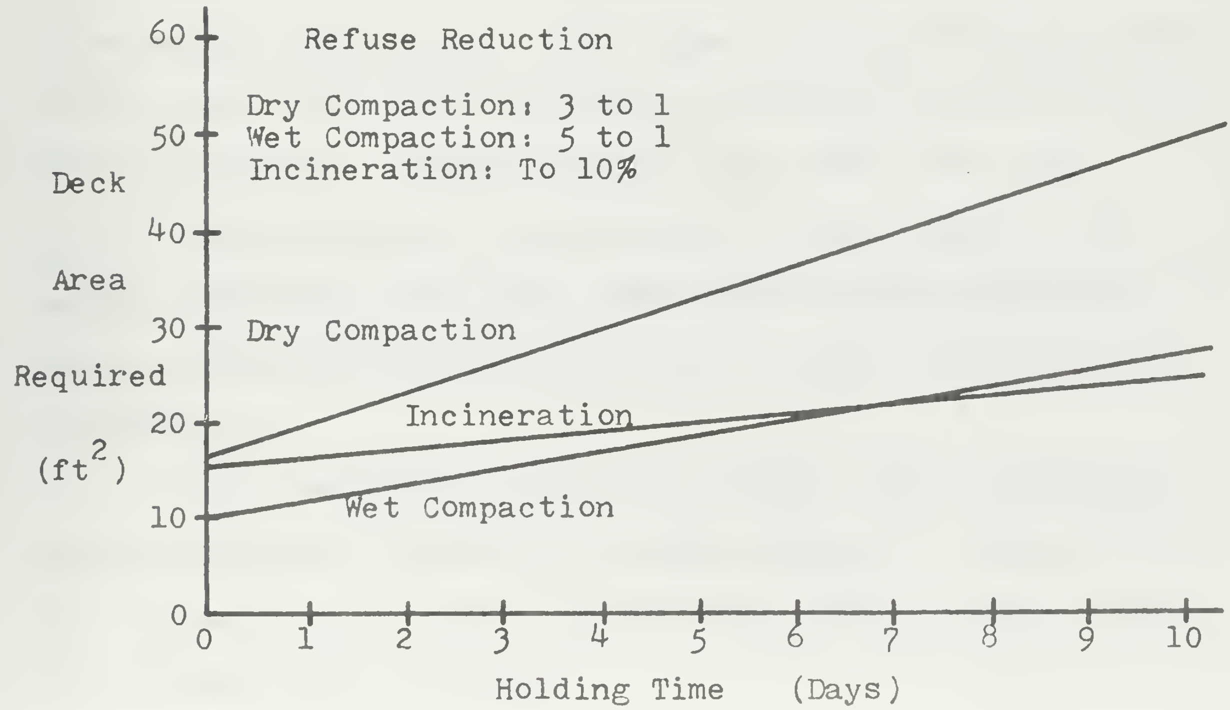
It is concluded from this analysis that incineration is the best primary method of shipboard solid waste disposal.

FIGURE 1

COMPARISON OF WEIGHT AND DECK AREA

REQUIRED BY SOLID WASTE DISPOSAL METHODS





B. Sewage Wastes

Factor	(Weight)	Biological Rating	Biological Score	Incineration/ Mechanical, Electro-Chemical Rating	Incineration/ Mechanical, Electro-Chemical Score	Holding Tank/ Recirculating Rating	Holding Tank/ Recirculating Score
S	(0.17)	3	0.51	3	0.51	4	0.68
R/M	(0.15)	2	0.30	3	0.45	3	0.45
C	(0.13)	2	0.26	4	0.52	4	0.52
H	(0.13)	3	0.39	4	0.52	3	0.39
SCP	(0.15)	4	0.60	4	0.60	2	0.30
A	(0.05)	2	0.10	4	0.20	3	0.15
W	(0.04)	2	0.08	4	0.16	3	0.12
FU	(0.06)	3	0.18	3	0.18	3	0.18
DR	(0.05)	2	0.10	3	0.15	3	0.15
F	(0.07)	3	0.21	3	0.21	2	0.14
Total	(1.00)	-	2.73	-	3.30	-	3.08

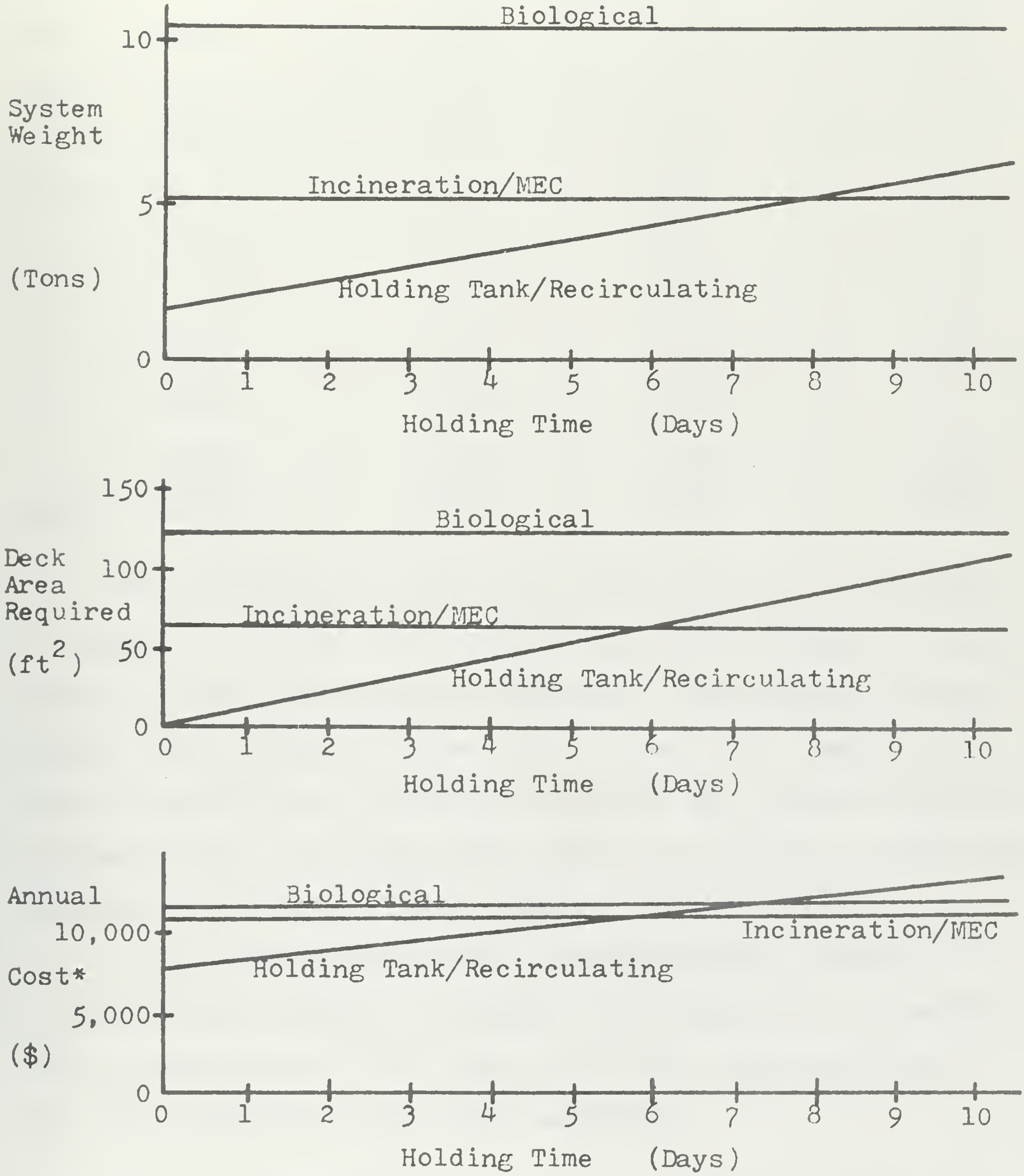
The evaluation of these systems compares with the Booz-Allen Report (25), except that longer holding times required by the model ship make the Holding Tank/Recirculating concept less attractive. Information was also taken from (16).

The quantitative relationships between systems for weight, deck area, and cost, based on a 175 man capacity system and taken from data presented in (25), are presented in Figure 2.

It is concluded from this analysis that a mechanical, electro-chemical incineration system, similar to that of the Colt Industries' proposal, is the best primary method of shipboard sewage waste disposal.

FIGURE 2

COMPARISON OF WEIGHT, DECK AREA REQUIRED, AND ANNUAL COST OF SEWAGE WASTE DISPOSAL METHODS (25)



*Assuming 10 year life and placement on an existing vessel.

C. Ballast, Bilge, and Machinery Discharges

Factor	(Weight)	Settling Rating	Settling Score	Flotation Rating	Flotation Score	Coalescer/Filter Rating	Coalescer/Filter Score
S	(0.17)	3	0.51	2	0.34	3	0.51
R/M	(0.15)	3	0.45	2	0.30	3	0.45
O	(0.13)	3	0.39	2	0.26	3	0.39
H	(0.13)	3	0.39	2	0.26	3	0.39
SOP	(0.15)	3	0.45	2	0.30	3	0.45
A	(0.05)	2	0.10	2	0.10	4	0.20
W	(0.04)	2	0.08	2	0.08	4	0.16
FU	(0.06)	3	0.18	3	0.18	4	0.24
DR	(0.05)	3	0.15	3	0.15	3	0.15
F	(0.07)	3	0.21	2	0.14	4	0.28
Total	(1.00)	-	2.91	-	2.11	-	3.22

The evaluation of these oil-water separation processes is somewhat difficult, since there is a wide variance in their ability to meet the required standards. Information on these methods came principally from (28, 29, and 34). Quantitative data on settling and flotation devices of the capacity desired are sketchy, but it appears that they are an order of magnitude larger than coalescer/filter units of the same capacity.

It is concluded that the coalescer/filter process is the best primary method of disposal for shipboard oily wastes. This is supported by (30), which calls the coalescer/filter "the most effective" oily water separator.

This concludes the suboptimization process within the

individual areas. Area and method overlap will now be investigated to see if the areas may be integrated in any way and to see if the methods may be improved by the addition of secondary methods.

The incineration process overlaps all three areas, since it may be used to dispose of solid wastes, sewage solids, and waste oil. The waste oil, furthermore, is attractive as a primary or, at least, secondary fuel source for the incineration process. Therefore, in order to consolidate the total system, a single incinerator to service all three areas is considered desirable.

Garbage or food wastes may be handled in a manner similar to the sewage solids. The use of parts of the sewage system on these solid wastes is also considered desirable. No other area overlaps are apparent.

Each of the primary methods of disposal chosen in the systems analysis may be made more efficient by combining them with one or more secondary methods. The sewage disposal system, for example, being more highly developed, is already in a system form. It consists, basically, of a solid-liquid separator, an incinerator for sewage solids treatment, a holding tank, and a chloroflotator for sewage liquid treatment. This shows an integration of separate methods into an efficient system.

The incineration of solid wastes can be improved by using size reduction equipment in the form of a shredder for trash and grinders for garbage. Dryers, however, are not

considered to be economical (9). Hand separation techniques should be sufficient for this area, and ash removal from the incinerator can also be manual. Some storage of ash and non-combustibles is necessary.

Settling occurs naturally in the ship's ballast tanks. Advantage may be taken of this along with more efficient emptying of fuel from the tanks to aid the coalescer/filter process. A means of measuring the 100 ppm limit, and a dirty oil tank for storage of the separated oil will also be required.

It is not felt that the addition of the secondary items described would degrade any of the primary methods of disposal to the point that another method of disposal would be more desirable. Therefore, the combination of methods described in the preceding paragraphs is felt to be the optimum pollution control system for the model ship.

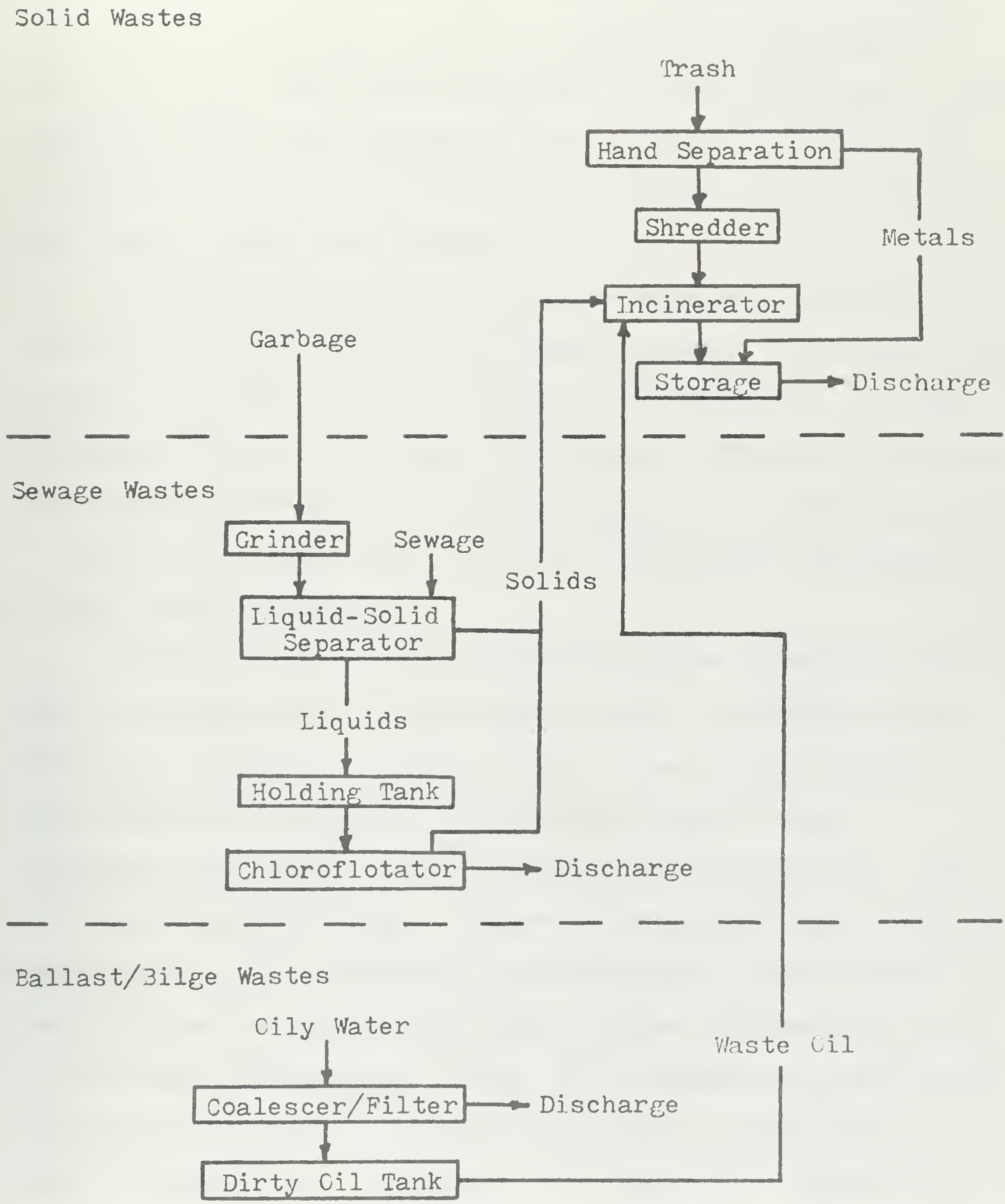
The accumulation of ash and possibly waste oil over a period of time will require some means of offloading them. Discharge of ash and non-combustibles at sea may be considered, since studies (10) of dumping incinerated municipal wastes at sea find no harm done to the environment and relatively quick disintegration. For long in port periods, minimal use of shore facilities or a sludge barge could be arranged.

Costs of the system components have not been discussed. It is felt that costs were not an overriding consideration.

A schematic of the pollution control system chosen for the model ship is presented in Figure 3.

<u>FIGURE 3</u>

PCLLUTICN CONTRCL SYSTEM SCHEMATIC



SYSTEM SIZING

The objective of this section is to attempt a rough design study of the components selected, so that their capacities may be determined, and the weight and space penalties incurred by the model ship estimated. A detailed design of the components will not be attempted here, primarily because the development of many of the components is not yet complete, and many minor changes are foreseen.

The incineration system must be capable of servicing the solid wastes as well as the sewage solids. This works out to about 375 #/day of solid wastes and approximately 30 #/day of sewage solids, for a total of 405 #/day. Thus, an incinerator operating 24 hours a day would require a 17 #/hour capacity to service the model ship. This is a relatively low capacity by most design standards.

Several variations of incinerators are presently available, including water or refractory walled, fluidized bed or grate, and retort or multiple chamber. Use of such methods as high temperature oxidation or pyrolysis have not been considered mainly due to their present state-of-the-art, cost, and limited applicability. The use of water walls at such low capacities is not considered to be economical, and the use of the fluidized bed aboard ship adds a degree of complexity that is considered undesirable. Corey (8) recommends a retort type incinerator for such low capacities, since it offers the greatest compactness, structural efficiency, and combustion efficiency. The smallest incinerator of this type presented

has a capacity of 50 #/hour. This would be required to operate only 30% of the day, allowing about 70% down time for maintenance and cleaning.

A steel cased, refractory lined incinerator, with cast iron grates and an air pollution control device, of this capacity is about 4 feet on a side, requiring 16 square feet of deck space, about 65 cubic feet in volume, and weighs an estimated 1.5 tons. Data on incinerator weight is extremely scarce. This figure was obtained by dimensionally scaling down a 200 #/hour incinerator presented in (36).

One shredder and three garbage grinders are considered necessary for the model ship. From (9) and household figures, these are estimated to require a total of 5 square feet in deck space, 20 cubic feet in volume, and to weigh 0.5 tons.

Storage space is also required for incineration ash. The ash from incineration for an entire patrol would weigh about 1.5 tons. This would require approximately 200 cubic feet in volume and 25 square feet in deck area, if an 8 foot compartment height is assumed. This could be reduced by dumping at sea or by offloading in barrels to shore facilities, when available, in port.

The sewage treatment system must serve 150 men as well as handle garbage. An average of 30 gallons/man/day of sewage combined with 5 gallons/man day of garbage (36) requires a system capacity of at least 5250 gallons/day. The 175 man Colt Industries' unit has a capacity of 5800 gallons/day. This allows a 13% margin, which should be sufficient

even at maximum flow rates.

This unit, less the incinerator which is now considered separately, consists of the chloroflotator, a holding tank, a solids separator and transfer unit, a hypochlorite storage unit, and associated piping. The chloroflotator separates suspended solids and produces chlorine for disinfection purposes. Electrolysis of sodium chloride, present in sea water, forms sodium hydroxide and hydrogen at the cathode and chlorine and oxygen at the anode. As fine gaseous bubbles, these attach themselves to and float solid particles to the liquid surface, where they may be removed. This system is estimated to require 20 square feet of deck space, 110 cubic feet in volume, and to weigh about 2.5 tons, when fully loaded.

The coalescer/filter unit should be required to have a 600 gallon/minute capacity from a deballasting standpoint. A unit consisting of two 300 gallon/minute primary separators with six coalescing screens each, a fiberglass cartridge polishing filter unit, and a probe for detecting the 100 ppm limit is still in the development stages. Realistic target figures are considered to be: 35 square feet of deck area, 200 cubic feet in volume, and a weight of 8 tons, wet (34). The dry weight of this unit is estimated to be about 4 tons, from comparison with other coalescer/filter units.

In addition, storage is required for dirty oil. The model ship presently has a dirty oil tank, 5-192-2-F, of 3790 gallons capacity. This is considered to be more than sufficient to meet the needs of the shipboard pollution control

system.

A summary of the weights and the space required by the various system components is presented in Table X.

TABLE X

SUMMARY OF CAPACITY, WEIGHT, AND

SPACE REQUIRED BY SYSTEM COMPONENTS

Components	Capacity	Weight (tons)	Area (sq. ft.)	Volume (cu. ft.)
Incinerator	50 #/hr	1.5	16	65
Shredder/Grinders	-	0.5	5	20
Ash Storage	-	1.5	25	200
Sewage Treatment System	5800 gal/day	2.5	20	110
Coalescer/Filter Unit	600 gal/min	8.0	35	200
Dirty Oil Tank	3790 gallons	12.0*	65*	500*
Totals		26.0	166	1095

*Not considered as a penalty to the ship, since this is presently available on board.

EFFECT OF SYSTEM ON SHIP STABILITY AND OTHER CHARACTERISTICS

The previous section has shown that in order to accommodate the pollution control system the ship must carry extra weight and provide a certain amount of extra space. The penalty incurred by the vessel for carrying the system will be that weight and space she must accommodate above and beyond that which she already provides. Some adjustment must be made to the totals arrived at in Table X to obtain the real penalty for carrying this system. First, the dirty oil tank is not considered to be a penalty, since this is already provided by the ship. Also, the weight of new piping and structural adjustments has not been considered. It is felt that this weight would be cancelled by the removal of the present bilge water separator, by considering the oily water in the coalescer/filter as a penalty when in actuality it is ballast water already carried, and by taking the full penalty for ash storage when it will normally be less. With these adjustments, the weight and space penalties to the model ship are: 14.0 tons weight, 101 square feet deck area, and 595 cubic feet volume.

The weight penalty of 14.0 tons represents only 0.48% of the ship's full load displacement of 2953 tons. This is not considered significant, since the parallel sinkage resulting from this weight addition would be about one-half inch.

To insure adequate ship stability, (3) requires the model ship to maintain a minimum metacentric height, GM. If

the height of the ship's metacenter, KM, is known for all drafts, a limiting ship's center of gravity, KG, may be obtained. For the model ship at full load displacement, the maximum allowable KG is 18.07 feet. The normal KG at this displacement is 16.94 feet. Thus, using the standard formula for computing the change in the ship's center of gravity for a weight addition, the following expression can be written:

$$\frac{2953\ (16.94)\ +\ 14\ (X)}{2967} = 18.07$$

where X represents the highest acceptable value of the system center of gravity.

Solving this equation for X, it is found that the system center of gravity must be less than 250 feet above the keel. Obviously there is not much danger of reducing the ship's GM to an unacceptable value as a result of adding the pollution control system.

Two other properties are also of interest. The trim of the vessel is affected by the longitudinal placement of the system fore and aft, and heel is affected by placement of the system athwartships in relation to the ship's centerline. Using the values of Moment to Trim One Inch and Moment to Heel One Degree, at the full load displacement, it is found that the system center of gravity must be 39.4 feet from the ship's longitudinal center of flotation, LCF, to trim the ship one inch, and 10 feet off the ship's centerline to heel the ship one degree.

The values used in this analysis do not change significantly throughout the vessel's operating range. A summary

of the vessel's characteristics over this range is presented in Table XI.

It is concluded that the placement of the pollution control system on the model ship will not impair its stability.

The next area to investigate is the space available on board the model ship. As mentioned previously, the model ship presently has a Dirty Oil Tank, 5-192-2-F. The vessel also has a Sewage Sump and Ejector Compartment, 5-144-0-Q, for the purpose of an anticipated sewage system. This compartment provides approximately 335 square feet of deck space, and about 3400 cubic feet in volume. This is more than is required by the pollution control system. Therefore, with this compartment alone, the model ship has the necessary space to accommodate the proposed pollution control system.

One possible arrangement of the system in compartment 5-144-0-Q is shown in Figure 4. This arrangement locates the heavier components in the after section of the compartment to minimize trim, since the compartment center is 40 feet forward of the LCF. As arranged, the system longitudinal center of gravity is at frame 159, and the system vertical center of gravity is about 7 feet above the keel. This results in less than one inch of trim by the bow. The symmetrical arrangement should induce no heel, and since the system's vertical center of gravity is less than KG, the GM of the model ship will be increased.

A summary of the model ship's characteristics after placing the system on board is presented in Table XI, also.

TABLE XI

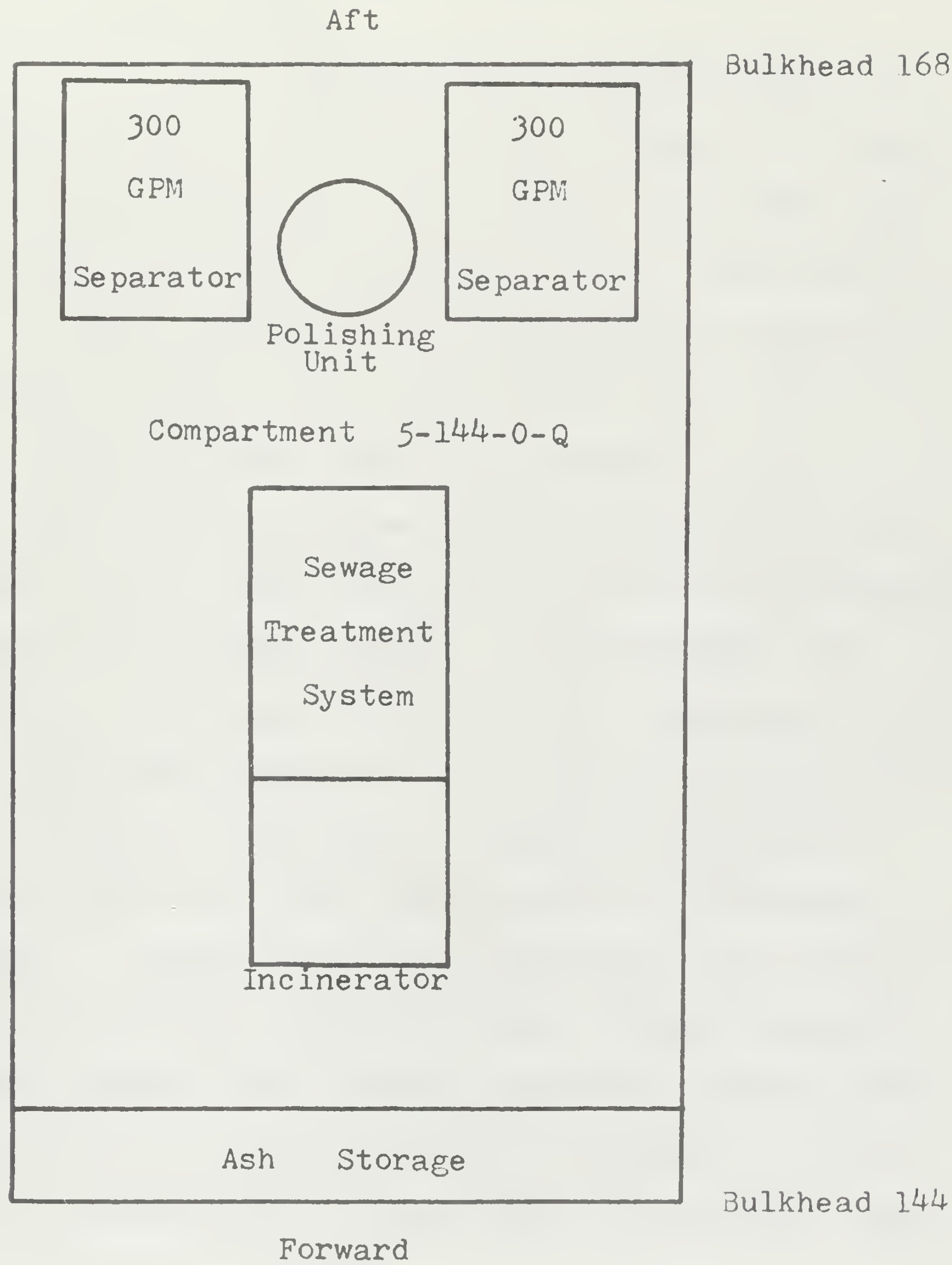
MODEL SHIP CHARACTERISTICS

Present:	Full Load	Minimum Operating Condition
Displacement	2953 tons	2909 tons
KM	20.66 feet	20.74 feet
KG	16.94 feet	16.97 feet
Max. Effective KG	18.07 feet	18.09 feet
LCF (aft of midships)	21.00 feet	21.05 feet
Moment to Trim 1"	551 foot-tons	548.5 foot-tons
Moment to Heel 1°	140 foot-tons	147 foot-tons
Tons per Inch Immersion	26.6	26.5
Draft Forward	13'-11"	14'- 2"
Draft Aft	14'- 5"	14'- 0"

After System:	Full Load	Minimum Operating Condition
Displacement	2967 tons	2923 tons
KM	20.64 feet	20.71 feet
KG	16.90 feet	16.91 feet
Max. Effective KG	18.07 feet	18.09 feet
LCF (aft of midships)	19.98 feet	21.03 feet
Moment to Trim 1"	552 foot-tons	549.5 foot-tons
Moment to Heel 1°	137.5 foot-tons	144.5 foot-tons
Tons per Inch Immersion	26.6	26.5
Draft Forward	14'- 0"	14'- 3"
Draft Aft	14'- 5"	14'- 0"

FIGURE 4

POSSIBLE ARRANGEMENT OF THE SYSTEM ON THE MODEL SHIP



CONCLUSIONS AND RECOMMENDATIONS

As a result of this study of designing a pollution control system for the Coast Guard, 378' high endurance cutter, several conclusions have been reached and appropriate recommendations can be made.

First, it is concluded that three distinct areas of shipboard water pollution exist: (1) solid wastes; (2) sewage wastes; and (3) oil pollution. In addition, two other areas of shipboard pollution exist and have not been dealt with in this thesis. These are thermal pollution and air pollution. While the former appears to be insignificant, the latter is significant, highly visible, and will require control.

This thesis also concludes that the optimum pollution control system for the model ship would include an incinerator for solid wastes and sewage solids, a chloroflotator for sewage liquids, a coalescer/filter unit for ballast and bilge water, and associated equipment. This selection is based to some degree on present technology. Shipboard pollution control devices are not of the type that can be purchased "off the shelf." Further research, development, and testing are required even for the items selected. Future research and development should also include many of the methods that were not considered as primary methods of disposal in this thesis, since breakthroughs in such areas as "membranes" may present more desirable solutions.

In choosing a pollution control system for a ship, in general, there appear to be several parameters which govern

the system applicable to any particular ship. Ship size, for example, controls the relative size and weight that can be afforded to a system of this type. The number of crew members is also a determining factor in the size of the system, especially for sewage treatment systems. The vessel's operating schedule has an effect on the type of system chosen, since ships with short in port times may take optimum advantage of holding concepts. The type of vessel also dictates the system qualities desired. Fleet oilers and repair ships present varied requirements. Finally, at present, vessel age must be considered to evaluate the extent of the system required, probably on a cost basis.

The investigation and selection of the components for the model ship's system leave many questions unanswered. These questions must be the object of future research in this area.

The first major area of concern deals with the solid wastes. The basic question is: Is an upgrading of present methods necessary? The answer for the future appears to be: Yes. If this is so, a much more extensive survey of the quantities and properties of solid wastes will be required. Further research on methods of disposal will also be required. Incineration methods, which provide the greatest size and weight reduction for refuse, also impose a high initial space and weight penalty upon the ship. Holding times of 7-8 days are required before any advantage is felt on this basis. This time might be reduced if combustible containers were

used whenever practicable, in order to reduce the amount of metals and non-combustibles stored. The type of incinerator also requires development. It must be able to handle solid wastes as well as sewage solids, which have a much higher moisture content. While drying is considered uneconomical for solid wastes, it may be required for sewage solids. The quality of waste oil which may be used in an incinerator must also be investigated, and the degree of automation determined.

In the area of sewage wastes, system size appears to be the major problem. Since this is highly dependent on the number of crew members, future requirements must be anticipated in design. In addition, as an alternative to the system selected for the model ship, holding tanks may be considered. From an extension of the Booz-Allen Applied Research, Inc. figures, these lose their advantage after 6-8 days of holding time. Also, only the discharges from water closets and urinals were treated in this thesis. While it does not appear that other discharges mentioned in this area require treatment, this must be explored further, since some may require filtering.

Further development and testing is required in the ballast, bilge, and machinery discharge area, but the coalescer/filters should be a workable solution in the near future. Stripping of fuel tanks should be considered to reduce the amount of oil remaining in the tanks to be ballasted, if necessary. The discharge of salty evaporator discharge to the bilges increases the bilge water problem. A direct over-

board discharge should be investigated. In addition, cooling water was not specifically treated in this thesis. Discharges of this type may require treatment, and monitoring, at least by eye since the 100 ppm limit is the visible threshold, should be considered.

The investigation of stability, weight carried, and space afforded by the model ship found no apparent difficulty in carrying the selected system on board. The penalties for fuel required by the system as well as the extra fuel burned in propelling a heavier ship, and the electrical power required by the system must also be determined. While these requirements appear to be well within the capability of the model ship, they must be considered when selecting systems.

The final conclusion of this thesis is that the problem of shipboard pollution is a very real one. It can best be solved by an integrated systems approach which considers all aspects of the problem and results in a centralized system. Such a system would best enable the ship to execute the missions for which it was designed, without adversely affecting the environment.

REFERENCES

1. Guide for the Disposal of Shipboard Wastes, Technical and Research Bulletin 3-13, The Society of Naval Architects and Marine Engineers, New York, September 1962.

2. Technical-Economic Study of Solid Waste Disposal Needs and Practices, Combustion Engineering Inc., Windsor, Connecticut, 1969.

3. Damage Control Book, High Endurance Cutter WHEC 715, United States Coast Guard, Washington, D.C., 1967.

4. Solid Waste Processing: A State-of-the-Art Report on Unit Operations and Processes, Battelle Memorial Institute, Columbus, Ohio, 1969.

5. Summer Study on the Management of Solid Wastes, Final Report, Vol. I, ed. D.G. Wilson, M.I.T., 1968.

6. Whiston, D., Searching for Answers to Refuse Handling, M.I.T., 1969.

7. Hershaft, A., "Solid Waste Treatment," Science and Technology, June 1969.

8. Principles and Practices of Incineration, ed. R.C. Corey, Wiley, 1969.

9. Petkun, R.L., An Analysis of Solid Refuse Combustion Systems, M.S. Thesis, Chemical Engineering Department, M.I.T., 1969.

10. First, M.W., "Waste Incineration at Sea and Ocean Disposal of Non-floating Residues," 62nd Annual Meeting of the Air Pollution Control Association, New York, 1969.

11. Technical Manual for Conservomatic Solid Waste Disposal Systems, Conservomatic Corp., Oreland, Pennsylvania.

12. U.S. Congress, Wastes from Watercraft, Senate Document No. 48, 90th Congress, 1st Session.

13. Jakobson, K. and M.J. Posner, Survey to Determine Quantities and Properties of Sewage from Naval Vessels, U.S. Navy Marine Engineering Laboratory Research and Development Report 346/64, January 1965.

14. Kurtz, U.I., "Sewage Pollution from River Towboats," Marine Technology, October 1967.

15. Degler, S.E. and S.C. Bloom, Federal Pollution Control Programs: Water, Air, and Solid Wastes, Washington, D.C., 1969.

16. Singerman, H.H. and E.T. Kinney, "The Navy's Technological Progress in Water Pollution Abatement," Naval Engineers Journal, October 1968.

17. Weldco Self-contained Unit for the Automatic Processing of Sewage Waste, The Youngstown Welding and Engineering Company, Youngstown, Ohio.

18. Cardinal, P.J., "The Incinerator's Role in Sludge Disposal," The American City, December 1967.

19. Marine Sewage Treatment Systems, Bulletin MS-1, Colt Industries, Fairbanks Morse Pump and Electric Division, Kansas City, Kansas.

20. Sewage Treatment Plant, Shipboard, Ship Systems Command Contract Specification, SHIPS-S-5454, August 1969.

21. Jakobson, K., Evaluation of a Shipboard Sewage Treatment System, U.S. Navy Marine Engineering Laboratory Evaluation Report 104/66, March 1966.

22. Sewage Treatment Equipment, Chlorinator-Macerator, Military Specification, MIL-S-24201A (SHIPS), December 1968.

23. Stokes, J.H., "Pollution of the World's Harbors, Docks, and Inland Waterways, with Particular Reference to Ships," Marine Technology, January 1971.

24. Hertzberg, R.H., "Waste Disposal from Watercraft," Water Pollution Control Federation Journal, December 1968.

25. Phase II Final Report on Naval Ship Waste Disposal Study, Booz-Allen Applied Research Inc., Bethesda, Maryland, 1969.

26. Clingan, T.A., Jr., "Oil Pollution, No Solution?," U.S. Naval Institute Proceedings, Vol. 95, No. 5, May 1969.

27. "Keeping Oil Out of the Sea: What's Going On and What's Ahead," Ocean Industry, November 1967.

28. Yu, T.S. and D.R. Ventriglio, Shipboard Oil Pollution Control Systems for Ballast and Bilge Waters: A State-of-the-Art Search, Naval Ship Research and Development Laboratory Report, MATLAB 244, 1969.

29. Glazer, M., "The Shipping Industry," Waste Disposal Problems in Selected Industries, ed. J.E. Ullmann, Hofstra University, 1969.

30. Matogn, I., "A Soviet Contribution to Oil Pollution Control," Shipbuilding and Shipping Record, September 6, 1968.

31. "Britain Claims World Lead in Beating Oil Menace," Safety at Sea International, September/October 1970.

32. "Laws on Oil Pollution Will Be More Severe," Safety at Sea International, May/June 1970.

33. Clyne, R.W., "Mechanical Retrieval of Waste Oils and Solids from Water," 23rd ASLE Annual Meeting in Cleveland, May 6-9, 1968.

34. Research and Development for a Shipboard Oil/Water Separation System, Permutit Co., U.S. Maritime Administration Contract MA 2722, December 1966.

35. Sipple, H.L., J.F. Hamma, and W.H. Key, Fleet Pollution Control System (FLEPOCS), 13.71 Report, M.I.T., January 1970.

36. Reese, R.M., G.R. Laughlin, and H. Schmidt Jr., Fleet Pollution Control Ship Concept, 13.71 Report, January 1970.

37. Rickles, R.N., Pollution Control, Noyes Development Corp., New York, 1965.